7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (See Figure 7-1). Landfills are the nation's largest source of anthropogenic methane emissions, accounting for 33 percent of the U.S. total.[1] Waste combustion is the second largest source in this sector, emitting carbon dioxide (CO_2) and nitrous oxide (N_2O). Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 1998 Waste Chapter GHG Sources

Overall, in 1998, waste activities generated emissions of 65.4 MMTCE, or 3.6 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**59.1**	**59.0**	**60.0**	**60.5**	**60.8**	**61.4**	**61.1**	**61.1**	**59.7**
Landfills	58.2	58.1	59.1	59.6	59.9	60.5	60.2	60.2	58.8
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N_2O	**2.1**	**2.1**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Human Sewage	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO_2	**2.8**	**3.0**	**3.0**	**3.1**	**3.1**	**3.0**	**3.1**	**3.4**	**3.5**
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5
Total	**64.0**	**64.1**	**65.1**	**65.7**	**66.1**	**66.6**	**66.4**	**66.7**	**65.4**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
CH_4	**10,320**	**10,303**	**10,475**	**10,557**	**10,608**	**10,724**	**10,667**	**10,671**	**10,430**
Landfills	10,170	10,151	10,321	10,401	10,451	10,566	10,507	10,509	10,267
Wastewater Treatment	150	151	153	155	156	158	159	161	162
N_2O	**24**	**24**	**25**	**25**	**26**	**25**	**26**	**26**	**26**
Human Sewage	23	24	24	24	25	25	25	25	25
Waste Combustion	1	1	1	1	1	1	1	1	1
CO_2	**10,344**	**10,931**	**10,992**	**11,295**	**11,307**	**11,104**	**11,504**	**12,531**	**12,889**
Waste Combustion	10,344	10,931	10,992	11,295	11,307	11,104	11,504	12,531	12,889

Note: Totals may not sum due to independent rounding.

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[1] Landfills also store carbon from biogenic sources, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in Chapter 6.

Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 1998, landfill emissions were approximately 58.8 MMTCE (10,268 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 93 percent of total landfill emissions, while industrial landfills accounted for the remainder. Landfills also emit non-methane volatile organic compounds (NMVOCs). There are over 2,300 landfills in the United States (BioCycle 1999), with the largest landfills receiving most of the waste and generating the majority of the methane.

Methane emissions result from the decomposition of organic landfill materials such as paper, food scraps, and yard trimmings. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste is initially digested by aerobic (i.e., in the presence of oxygen) bacteria. After the oxygen supply has been depleted, the remaining waste is attacked by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane-producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent methane, by volume.[2] Methane production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

[Begin Text Box]

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO_2 emissions from the combustion or degradation of biogenic materials is important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of grass clippings or combustion of paper). The carbon contained in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would eventually degrade and cycle back to the atmosphere as CO_2. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Thus, if CO_2 emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) result from materials grown on a sustainable basis, then those emissions are considered to mimic the closed loop of the natural carbon cycle —that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. Conversely, CO_2 emissions from burning fossil fuels or products such as plastics derived from fossil sources would not enter the cycle were it not for human activity (i.e., they were removed from permanent fossil deposits). Likewise, CH_4 emissions from landfilled waste would not be emitted were it not for the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills.

However, the removal of carbon from this cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of sustainable, biogenic origin (e.g., yard trimmings) are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987).

that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 19 MMTCE and 2 to 5 MMTCE per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in Chapter 6 to comport with IPCC inventory reporting guidance regarding the tracking of carbon flows.

 [End Box]

[Begin Text Box]

Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks

U.S. waste management patterns changed dramatically in the 1990s in response to changes in economic and regulatory factors. Perhaps the most significant change from a greenhouse gas perspective was the increase in the national average recycling rate, which climbed from 16 percent in 1990 to 28 percent in 1997 (EPA 1999).

This change had an important effect on emissions in several areas, primarily in regard to emissions from waste and energy activities, as well as forestry sinks. The impact of increased recycling on greenhouse gas emissions can be best understood when emissions are considered from a life cycle perspective (EPA 1998). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed and managed as waste. The substitution of recycled inputs for virgin inputs reduces three types of emissions throughout the product life cycle. First, manufacturing processes involving recycled inputs generally require less energy than those using virgin inputs. Second, the use of recycled inputs leads to reductions in process non-energy emissions. Third, recycling reduces disposal and waste management emissions, including methane from landfills and nitrous oxide and non-biogenic carbon dioxide emissions from combustion. In addition to greenhouse gas emission reductions from manufacturing and disposal, recycling of paper products—which are the largest component of the U.S. wastestream—results in increased forest carbon sequestration. When paper is recycled, fewer trees are needed as inputs in the manufacturing process; reduced harvest levels result in older average forest ages, with correspondingly more carbon stored.

[End Box]

Between 1990 and 1998, methane emissions from landfills were relatively constant (see Table 7-3 and Table 7-4). The roughly constant emissions estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators also increased, thereby reducing emissions.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) composition of the waste-in-place; (3) the amount of methane that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Gg in 1990 to 5,907 Gg in 1998, an increase of 20 percent (see Annex J). During this period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1,110 Gg of methane was recovered and combusted (i.e., used for energy or flared) from landfills. In 1998, the estimated quantity of methane recovered and combusted increased to 3,590 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a recently promulgated regulation that requires large landfills to collect and combust landfill gas (Federal Register 1996).

Table 7-3: CH$_4$ Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
MSW Landfills	60.4	61.8	63.6	65.5	67.5	69.5	71.1	72.8	74.3
Industrial Landfills	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0	5.1
Recovered									
Gas-to-Energy	(4.6)	(4.9)	(5.2)	(6.0)	(6.8)	(7.1)	(8.0)	(9.2)	(11.6)
Flared	(1.7)	(3.0)	(3.6)	(4.4)	(5.5)	(6.7)	(7.8)	(8.3)	(9.0)
Net Emissions	**58.2**	**58.1**	**59.1**	**59.6**	**59.9**	**60.5**	**60.2**	**60.2**	**58.8**

Note: Totals may not sum due to independent rounding.

Table 7-4: CH$_4$ Emissions from Landfills (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998
MSW Landfills	10,550	10,791	11,107	11,431	11,777	12,138	12,419	12,705	12,974
Industrial Landfills	731	746	767	787	809	833	850	868	883
Recovered									
Gas-to-Energy	(811)	(861)	(915)	(1,053)	(1,183)	(1,233)	(1,397)	(1,608)	(2,025)
Flared	(299)	(524)	(637)	(764)	(952)	(1,171)	(1,363)	(1,454)	(1,564)
Net Emissions	**10,171**	**10,152**	**10,321**	**10,402**	**10,452**	**10,566**	**10,508**	**10,510**	**10,268**

Note: Totals may not sum due to independent rounding.

Methodology

Based on available information, methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, minus the methane oxidized before being released into the atmosphere, plus the methane produced by industrial landfills.

The methodology for estimating CH$_4$ emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. This model is based on the pattern of actual waste disposal by each individual landfill surveyed by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population (EPA 1993). For each landfill in the data set, the amount of waste-in-place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex J.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, and a database compiled by the EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the methane combusted by the 235 flares in operation from 1990 to 1998 were estimated. This estimate likely underestimates emissions. The EPA believes that more than 700 flares exist in the United States, and so the EPA is working with the Solid Waste Association of North America (SWANA) to better characterize flaring activities. Additionally, the LMOP database provided data on landfill gas flow and energy generation for 237 of the approximately 260 operational landfill gas-to-energy projects.

Emissions from industrial landfills were assumed to be equal to 7 percent of the total methane emissions from municipal landfills. The amount of methane oxidized was assumed to be 10 percent of the methane generated (Liptay et al. 1998). To calculate net methane emissions, methane recovered and oxidized was subtracted from methane generated at municipal and industrial landfills.

Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1991 through 1998 were obtained from *BioCycle* (1999). Documentation on the landfill methane emissions methodology employed is available in the EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990:*

Report to Congress (EPA 1993). Information on flares was obtained from vendors, and information on landfill gas-to-energy projects was obtained from the LMOP database.

Uncertainty

Several types of uncertainties are associated with the estimates of methane emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is lacking on the area landfilled and total waste-in-place—the fundamental factors that affect methane production. In addition, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty in the landfill methane emission rate is estimated to be roughly ±30 percent.

Waste Combustion

Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW). In 1996, there were approximately 137 municipal waste combustion plants in operation within the United States (EPA 1999). Most of the organic materials in MSW are of biogenic origin. Net CO_2 emissions resulting from combustion of biogenic materials are accounted for under Land-Use Change and Forestry (see Box 7-1). However, one component—plastics—is of fossil origin, and is included as a source of CO_2 emissions. Plastics in the U.S. wastestream are primarily in the form of containers, packaging, and durable goods. Some other materials in the waste stream (e.g., some textiles and rubber) are of fossil origin, but are not included in this estimate.

In addition, MSW combustion has been identified as a source of nitrous oxide (N_2O) emissions. N_2O emissions are dependent on the types of waste burned and combustion temperatures (De Soete 1993).

Carbon dioxide emissions have risen 25 percent since 1990, to about 3.5 MMTCE (12,900 Gg) in 1998, as the volume of plastics in MSW has increased (see Table 7-5 and Table 7-6). Nitrous oxide emissions from MSW combustion were estimated to be 0.1 MMTCE (1 Gg) in 1998, and have not changed significantly since 1990.

Table 7-5: CO_2 and N_2O Emissions from Waste Combustion (MMTCE)

Year	CO_2	N_2O
1990	2.8	0.1
1991	3.0	0.1
1992	3.0	0.1
1993	3.1	0.1
1994	3.1	0.1
1995	3.0	0.1
1996	3.1	0.1
1997	3.4	0.1
1998	3.5	0.1

Table 7-6: CO_2 and N_2O Emissions from Waste Combustion (Gg)

Year	CO_2	N_2O
1990	10,000	1
1991	10,900	1
1992	11,000	1
1993	11,300	1
1994	11,300	1
1995	11,100	1
1996	11,500	1
1997	12,600	1
1998	12,900	1

Methodology

In the report, *Characterization of Municipal Solid Waste in the United States* (EPA 1999), the flows of plastics in the U.S. wastestream are reported for seven resin categories. The 1997 quantity generated, recovered, and discarded for each resin is shown in Table 7-7. The report does not provide estimates for individual materials landfilled and combusted, although it does provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and combusted, total discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. wastestream (76 percent and 24 percent, respectively).

Table 7-7: 1997 Plastics in the Municipal Solid Waste Stream by Resin (Thousand Metric Tons)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	1,724	4,200	1,198	4,881	2,531	1,905	3,030	**19,469**
Recovery	327	381	0	91	109	9	91	**1,007**
Discard	1,397	3,819	1,198	4,790	2,422	1,896	2,939	**18,462**
Landfill	1,061	2,903	910	3,641	1,841	1,441	2,234	**14,030**
Combustion	336	916	288	1,149	582	455	706	**4,432**
Recovery*	19%	9%	0%	2%	4%	0.5%	3%	**5%**
Discard*	81%	91%	100%	98%	96%	99.5%	97%	**95%**
Landfill*	62%	69%	76%	75%	73%	76%	74%	**72%**
Combustion*	19%	22%	24%	24%	23%	24%	23%	**23%**

* As a percent of waste generation.
Note: Totals may not sum due to independent rounding. PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE ((linear) low density polyethylene), PP (polypropylene), PS (polystyrene).

Fossil CO_2 emissions for 1997 were estimated as the product of plastic combusted, carbon content, and combustion efficiency (see Table 7-8). The carbon content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal the weighted average of the six categories. A combustion efficiency of 98 percent was assumed.

Table 7-8: 1997 Factors for Calculating CO_2 Emissions from Combusted Plastics

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted (Thousand Metric Tons)	336	916	288	1,149	582	455	706	**4,432**
Carbon Content of Resin	0.625	0.857	0.381	0.857	0.857	0.923	0.679[a]	**N/A**
Thousands of Metric Tons of Carbon Equivalent Combusted	210	785	110	985	498	420	479	**3,487**
Emissions (MMTCE)[b]	**0.21**	**0.77**	**0.11**	**0.97**	**0.49**	**0.41**	**0.47**	**3.42**

[a] Weighted average of other plastics.
[b] Assumes 98 percent combustion efficiency.
NA: Not applicable.

Emissions for 1990 through 1996 were calculated using the same approach. Estimates of the portion of plastics in the wastestream in 1998 were not available; therefore, they were projected by assuming 3 percent annual growth rate in generation and a 5.4 percent growth rate for recovery, based on reported trends (EPA 1999).

Estimates of N_2O emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997). According to this methodology, emissions of N_2O from MSW combustion is the product of the mass of MSW combusted, an emission factor of N_2O emitted per unit mass of waste combusted, and an N_2O emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 30 g N_2O/metric ton MSW, and an estimated emissions control removal efficiency of zero percent were used.

Data Sources

The estimates of CO_2 emissions and N_2O emissions are based on different data sources. The fossil CO_2 emissions are a function of a specific material—plastics—as reported by EPA (1999) in its characterization of the municipal wastestream. The N_2O emissions are a function of total waste combusted, as reported in the April 1999 issue of *BioCycle* (Glenn 1999). Table 7-9 provides MSW generation and percentage combustion data for the total wastestream. The emission factor of N_2O emissions per quantity of MSW combusted was taken from Olivier (1993).

Table 7-9: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Combusted (%)
1990	266,541,881	11.5
1991	254,796,765	10.0
1992	264,843,388	11.0
1993	278,572,955	10.0
1994	293,109,556	10.0
1995	296,586,430	10.0
1996	297,268,188	10.0
1997	309,075,035	9.0
1998	340,090,022	7.5

As noted above, CO_2 emissions from plastics are based on (1) the carbon content of the various plastic resins, and (2) an assumption of 98 percent combustion efficiency, as reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 1998).

Uncertainty

A source of uncertainty affecting both fossil CO_2 and N_2O emissions is the estimate of the MSW combustion rate. The EPA (1999) estimates of plastics generation, discards, and combustion are subject to considerable error. Similarly, the *BioCycle* (Glenn 1999) estimate of total waste combustion—used for the N_2O estimate—is based on a survey of state officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. Despite the differences in methodology and data sources, the two references— EPA's Office of Solid Waste (EPA 1999) and *BioCycle* (Glenn 1999)—provide estimates of total solid waste combusted that are relatively consistent (see Table 7-10).

Table 7-10: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,652,316
1991	30,236,976	25,479,677
1992	29,656,638	29,132,773
1993	29,865,024	27,857,295
1994	29,474,928	29,310,956
1995	32,241,888	29,658,643
1996	32,740,848	29,726,819
1997	32,294,240	27,816,753
1998	NA	25,506,752

NA (Not Available)

The other principal source of uncertainty for the carbon dioxide estimate is combustion efficiency. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. The value of 98 percent assumed here may not be representative of typical conditions.

As with other combustion-related sources of N_2O, emissions are affected by combustion conditions (De Soete 1993). In part, because insufficient data exists to provide detailed estimates of N_2O emissions for individual combustion facilities, the estimates presented are highly uncertain. The emission factor for N_2O from MSW combustion facilities

used in the analysis is a default used to estimate N_2O emissions from facilities worldwide (Olivier 1993). As such, it has a range of uncertainty of an order of magnitude (between 25 and 293 g N_2O/metric ton MSW combusted) (Watanabe, et al. 1992). Due to a lack of relevant information on the control of N_2O emissions from MSW combustion facilities in the United States, the estimate of zero percent for N_2O emissions control removal efficiency is also uncertain.

Wastewater Treatment

The breakdown of organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions. During collection and treatment, wastewater may be incidentally or deliberately managed under anaerobic conditions. The methane produced during deliberate anaerobic treatment is typically collected and flared or combusted for energy. However, whenever anaerobic conditions develop, some of the methane generated is incidentally released to the atmosphere. Untreated wastewater may also produce methane if contained under anaerobic conditions.

The organic content, expressed in terms of biochemical oxygen demand (BOD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. Under anaerobic conditions, wastewater with higher BOD concentrations will produce more methane than wastewater with lower BOD.

In 1998, methane emissions from municipal wastewater were 0.9 MMTCE (163 Gg). Emissions have increased since 1990 reflecting the increase in the U.S. human population. Table 7-11 provides emission estimates from domestic wastewater treatment.

At this time, data are not sufficient to estimate methane emissions from industrial wastewater sources. Further research is ongoing to quantify emissions from this source.

Table 7-11: CH_4 Emissions from Domestic Wastewater Treatment

Year	MMTCE	Gg
1990	0.9	150
1991	0.9	152
1992	0.9	154
1993	0.9	155
1994	0.9	157
1995	0.9	158
1996	0.9	160
1997	0.9	161
1998	0.9	163

Methodology

Wastewater methane emissions are estimated using the default IPCC methodology (IPCC/UNEP/OECD/IEA 1997). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.05 kilograms of wastewater BOD5[3] is produced per day and that 15 percent of wastewater BOD5 is anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.22 Gg CH_4/Gg BOD5.

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[3] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

Data Sources

National population data for 1990 to 1998 were supplied by the U.S. Census Bureau (1999). The emission factor employed was taken from Metcalf and Eddy (1972). Table 7-12 provides U.S. population and wastewater BOD data.

Table 7-12: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5
1990	249.3	4,554
1991	252.0	4,602
1992	254.9	4,655
1993	257.7	4,706
1994	260.2	4,752
1995	262.7	4,797
1996	265.1	4,842
1997	267.7	4,888
1998	270.2	4,935

Uncertainty

Domestic wastewater emissions estimates are highly uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences. It is also believed that industrial wastewater is responsible for significantly more methane emissions than domestic wastewater treatment.

Human Sewage

Sewage is disposed on land or discharged into aquatic environments such as rivers and estuaries. Prior to being disposed on land or in water, it may be deposited in septic systems or treated in wastewater treatment facilities. Nitrous oxide (N_2O) may be generated during each of these stages through nitrification and denitrification of the nitrogen that is present in sewage. Nitrification occurs aerobically and converts ammonium into nitrate, while denitrification occurs anaerobically, and converts nitrate into dinitrogen gas. Nitrous oxide is a gaseous intermediate product in the reaction sequences of both processes. In general, temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation from human sewage. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter (Metcalf and Eddy 1972). The amount of protein consumed by humans determines the quantity of nitrogen contained in sewage.

Nitrous oxide emission from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with one exception. The IPCC methodology assumes that N_2O emissions associated with land disposal and sewage treatment are negligible and all sewage nitrogen is discharged directly into aquatic environments. In the United States, however, a certain amount of sewage nitrogen is applied to soils via sewage sludge applications and therefore, not all sewage nitrogen enters aquatic environments.[4] The N_2O estimates presented here account for the amount of nitrogen in sewage sludge applied to soils.

Emissions of N_2O from sewage nitrogen discharged into aquatic environments were estimated to be 2.2 MMTCE (25 Gg N_2O) in 1998. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 10 percent in N_2O emissions from human sewage between 1990 and 1998 (see Table 7-13).

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[4] The IPCC methodology is based on the total amount of nitrogen in sewage, which is in turn based on human protein consumption and the fraction of nitrogen in protein (i.e., $Frac_{NPR}$). A portion of the total nitrogen in sewage in the United States is applied to soils in the form of sewage sludge each year. This amount is estimated as part of agricultural soil management (see Chapter 6) and is subtracted here from total nitrogen in human sewage to estimate sewage N_2O emissions.

Table 7-13: N$_2$O Emissions from Human Sewage

Year	MMTCE	Gg
1990	2.0	23
1991	2.0	24
1992	2.0	24
1993	2.0	24
1994	2.1	25
1995	2.1	25
1996	2.1	25
1997	2.1	25
1998	2.2	25

Methodology

With the exception described above, N$_2$O emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This is illustrated below:

$$N_2O(s) = [(Protein) \times (Frac_{NPR}) \times (NR\ People)] \times [1-Frac_{N\text{-}SOIL}] \times (EF) \times (^{44}/_{28})$$

Where:
N$_2$O(s) = N$_2$O emissions from human sewage
Protein = Annual, per capita protein consumption
Frac$_{NPR}$ = Fraction of nitrogen in protein
NR People = U.S. population
Frac$_{N\text{-}SOIL}$ = Fraction of sewage sludge N applied to soils
EF = Emission factor (kg N$_2$0-N/kg sewage-N produced)
(44/28) = The molecular weight ratio of N$_2$O to N$_2$

Data Sources

U.S. population data were taken from the U.S. Census Bureau (1999). Data on the annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 1999) (see Table 7-14). Because data on protein intake were unavailable for 1998, the value of per capita protein consumption for the previous year was used. An emission factor has not been specifically estimated for the United States, so the default IPCC value (0.01 kg N$_2$O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-14: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	249.3	39.2
1991	252.0	39.8
1992	254.9	40.1
1993	257.7	40.1
1994	260.2	41.0
1995	262.7	40.4
1996	265.1	40.8
1997	267.7	41.0
1998	270.2	41.0

Uncertainty

The U.S. population (NR people), per capita protein intake data (Protein), and fraction of nitrogen in protein (Frac$_{NPR}$) are believed to be fairly accurate. There is significant uncertainty, however, in the emission factor (EF) employed due to regional differences that would likely affect N$_2$O emissions but are not accounted for in the default IPCC factor. Moreover, the underlying methodological assumption that negligible N$_2$O emissions result from

sewage treatment may be incorrect. In addition N_2O emissions from industrial wastewater, which have not been addressed in the IPCC Guidelines, have not been estimated.

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 1998 are provided in Table 7-15.

Table 7-15: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996	1997	1998
NO_x	**83**	**86**	**87**	**112**	**103**	**89**	**87**	**89**	**NA**
Landfills	+	+	+	1	1	1	1	1	NA
Wastewater Treatment	+	+	+	+	+	+	+	+	NA
Waste Combustion[a]	82	85	86	107	99	88	86	87	NA
Miscellaneous[b]	+	1	1	4	3	1	1	1	NA
CO	**979**	**1,012**	**1,032**	**1,133**	**1,111**	**1,075**	**1,083**	**1,095**	**NA**
Landfills	1	1	2	2	2	2	4	4	NA
Wastewater Treatment	+	+	+	+	+	+	+	+	NA
Waste Combustion[a]	978	1,011	1,030	1,130	1,108	1,073	1,079	1,091	NA
Miscellaneous[b]	+	+	+	1	1	1	1	1	NA
NMVOCs	**895**	**907**	**916**	**949**	**949**	**968**	**388**	**394**	**NA**
Landfills	58	60	63	67	73	68	18	19	NA
Wastewater Treatment	57	58	61	63	64	61	57	58	NA
Waste Combustion[a]	222	227	230	256	248	237	237	240	NA
Miscellaneous[b]	558	562	563	563	564	602	76	77	NA

[a] Includes waste incineration and open burning (EPA 1999)
[b] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1998* (EPA 1999). This EPA report provides emission estimates of these gases by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

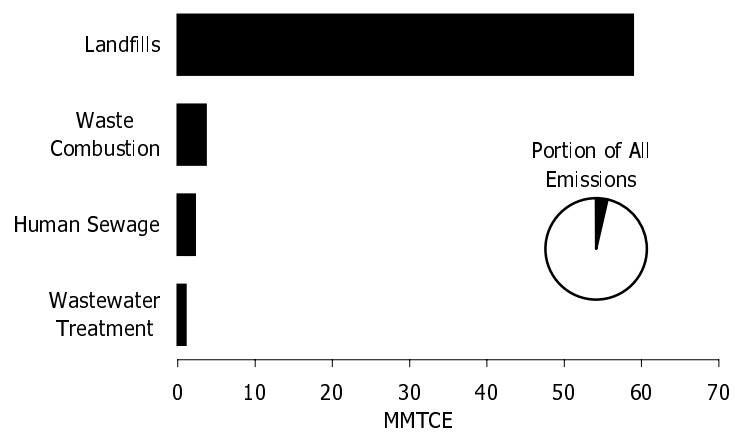Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Figure 7-1: 1998 Waste Chapter GHG Sources